# HAZARDS OF ALTITUDE TESTING AT AEDC

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**ABSTRACT** The detonability (explosion) hazards associated with testing large solid rocket motors in low pressure altitude chambers are largely unknown. Because of the potential damage to these unique facilities, quantification of the hazards involved in such testing is needed.

TRW performed an extensive analytical study to determine the probabilities of generating various explosive yields inside the J-4 vertical test cell at Arnold Engineering Development Center (AEDC) assuming that a failure occurred during an altitude test of a large solid propellant rocket motor (approximately 55,000 lbs of Class 1.3 propellant).

Three failure modes of significance were identified. Two involved axial ejection of the propellant grain downward toward the bottom of the test cell while the third involved radial ejection of the grain toward the test cell wall due to the internal gas pressure.

This paper describes the approach used to evaluate the key elements of the study: (a) identification of failure modes and the associated probability chain, (b) determination of the specific rocket motor initial (failure) conditions and parameters, (c) utilization of detonation theory and test results to develop a required impact velocity for detonation, correlation, (d) calculation of the fragment weight distribution and impact velocities and (e) development of statistical methods to determine the probability for each failure mode.

The results show that radial ejection contributes very little to the overall probability because of the large number of small fragments generated in this failure mode and that the axial failure mode probabilities decrease very rapidly with explosive yield. The overall result indicates that the probability of significant damage to other than the test cell itself is very low.

**INTRODUCTION** In the design and development of the upper stages of large solid rocket motors, test conditions close to actual flight can only be achieved at the unique altitude facilities currently available at Arnold Engineering Development Center (AEDC) in Tullahoma, Tennessee. These test cells, denoted J-4, J-5 and J-6, are large, expensive to build and repair and are a national resource because they do not exist anywhere else in the U.S. They provide the only means available for full stage static testing at altitude, other than actual flight testing.

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A 1982 accident in J-4 with a large diameter, class 1.3 rocket motor and another in J-5 with a class 1.1 motor in 1985, which resulted in an explosion, caused AEDC to be concerned with damage to nearby facilities and culminated in the fall of 1990 with the cessation of altitude testing of these motors at AEDC.

Because of the potential damage to the test cells and the surrounding, unique AEDC facilities, quantification of the detonability (explosion) hazards involved in low pressure altitude testing of solid rocket motors was needed. Therefore, an extensive analytical study was undertaken to determine the probabilities of generating various explosive yields inside the J-4 test cell assuming that a failure occurred during simulated altitude testing of a large rocket motor containing approximately 55,000 lbs of Class 1.3 propellant. The objective was to determine if it was safe to resume large diameter rocket motor altitude testing in test cell J-4.

**J-4 TEST CELL** The low pressure test cell consists of an above ground steel capsule which sets over the test stand and below which is a long diffuser tube through which the exhaust gases flow to the main underground chamber where the gases are deflected sideways by a conical steel plate called the "witches' hat". A layout of the cell is shown in Figure 1. The upper capsule is maintained at a low pressure (approximately 1.6 psi) while the lower chamber usually is at a higher pressure (5 - 7 psi) because of the exhaust gases and added cooling water.

For a motor case failure it is possible that propellant would be ejected radially outward to the capsule wall or ejected downward through the diffuser tube ultimately impacting the witch's hat. These are the events that actually took place in the 1985 and 1982 incidents, respectively. A detonation (or explosion; the words are used interchangeably) at the capsule wall might destroy it and allow blast waves to propagate to surrounding facilities causing significant damage. Likewise, detonation at the witches' hat will cause a blast wave to propagate up the diffuser tube, into the capsule, causing it to be removed or destroyed, and then to propagate to other facilities. In either case, the probability of such events needs to be determined.

**APPROACH** The objective of this study was to perform a hazards analysis to determine the risk associated with a detonation event in J-4. The specific goal is to determine the probability of exceeding a given explosive yield in J-4 (inside the capsule).

The approach involved the following key elements: (a) identify failure modes and the associated probability chain; (b) determine the specific rocket motor initial (failure) conditions and parameters; (c) utilize detonation theory and test results to develop a required impact velocity for detonation; (d) calculate the fragment weight distribution and impact velocities; (e) develop statistical methods to determine probability for each failure mode and compute the overall results.

**FAILURE MODES AND PROBABILITY CHAIN** Three failure modes were considered; Axial Full Grain Ejection, Axial Partial Grain Ejection and Radial Ejection. In the first mode, the cylindrical portion of the case unravels and the internal pressure in the space between the top of the grain and the case ejects the entire mass downward; acceleration is due both to gravity and the internal pressure above the grain. It is also possible that lower sections of the grain will break-up and fall away by their own weight, such that the remaining weight ejected downward is less than the full grain weight. In this axial partial grain ejection mode the same driving pressure will accelerate a lesser weight and thus yield a higher velocity than in the full grain case. In either case detonation at the witch's hat will cause a blast wave to propagate up the diffuser tube into the capsule, possibly causing it to be removed or destroyed and then to propagate to other facilities.

Radial ejection assumes that the failure causes the case to unravel and the cylindrical section of the case to "disappear" leaving an unsupported circular core cylinder of propellant having little strength to contain the internal core pressure. This failure leads to fragmentation of the propellant, acceleration of the fragments and multiple impacts at the capsule wall. Detonation at the capsule wall might destroy it and allow blast waves to propagate to surrounding facilities causing significant damage.

The weight ejected for all failure modes depends on the random variable time of failure and also, in the case of axial partial ejection, the fraction of the grain ejected.

The probability of these individual events must be properly combined to determine the overall probability of the explosive yield in J-4. This is given by the probability "chain" equation for the probability of a given weight or greater, detonating, which depends on the probability of a failure of any kind during a test (historically set at 0.02), the probability of an ejection of any kind given a failure (conservatively set equal to 1) and product probability terms representing the types of ejection discussed above. The first term of each product is the probability of the failure mode; the second is the probability of detonation of the given weight, or greater, in the capsule, given the failure mode.

The only unknown terms are the probability of detonation for each failure mode, and they are to be determined.

As described above, axial ejection results in impact at the witch's hat and these failure modes do not directly yield the (desired) weight detonating in the capsule. This was solved by correlating weight detonating at the bottom with (equivalent) weight detonating at the top and is discussed below.

**INITIAL CONDITIONS** The driving force for any ejection is the energy of the hot gas in the bore at the time of the failure. As the motor burns the internal volume increases, the weight of propellant and the web thickness decrease and the internal gas

(chamber) pressure and other thermodynamic properties vary in their characteristic fashion. Nominal burning conditions are assumed up until the time of the failure; then the chamber pressure is assumed to jump to an "upper limit" instantaneous pressure of 2835 psi at 0 sec (as recorded in the 1982 test which failed nearly at 0 sec) decreasing linearly to the $+3\sigma$ value at 15 sec. For times $\geq 15$ sec the upper limit follows the $+3\sigma$ curve. The pressure along these upper limit lines determines the acceleration of the propellant axially or radially.

**DETONATION THEORY** Each failure mode results in an impact event or events leading to the possibility of detonation of some or all of the propellant ejected. The velocity of the impact events is to be compared to that required for initiation of detonation of all or part of the propellant mass. For the axial cases a single large mass impacts the witch's hat while in the radial case a distribution of fragments impacts the inner capsule wall.

For large propellant masses critical geometry theory predicts the critical dimensions above which an initiated detonation will be sustained. Application to the propellant being considered indicates the grain is above critical and will sustain detonation. For initiation of detonation the required shock pressure for SDT (Shock-to-Detonation-Transition) generally ranges from about 25 kbar at critical dimensions to about 8 kbar at very large dimensions; for the particular motor being considered the value is about 12 kbar.

Initiation can also take place by XDT (Unknown-to-Detonation-Transition) under conditions less severe than for SDT. This might occur when a large propellant mass impacts a surface; the velocity required for initiation is less for XDT than for SDT. In this study it is assumed that XDT is SDT in unconsolidated (damaged) propellant caused by the impact. The damage to the propellant dynamically introduces porosity which is well known to significantly reduce the critical diameter and shock pressure requirement compared to consolidated propellant. The criterion is modified for XDT by defining a family of curves below the SDT criterion, for various values of porosity. This defines a more sensitive initiation criterion for XDT of approximately 3 kbar.

**DETONATION REQUIREMENTS AND DISTRIBUTION FUNCTION** Ullian[1] reported the "TNT Equivalent" of a series of aborted flights at the Eastern Space and Missile Center where various missile stages (Minuteman, Polaris, Poseidon) containing Class 1.3 propellant impacted various surfaces at various velocities. Results ranged from 1% to 100% TNT Equivalent. The XDT initiation proposed above is consistent with these data and when converted to an equivalent impact on steel (for convenience; the witches' hat and capsule are made of steel), the data provide a correlation of TNT equivalent versus impact velocity. Although this applies to a single large mass impacting in the axial ejection cases, the radial failure mode involves many, much smaller, fragments than the data reported by Ullian and a more general approach is required.

To do this, a large data base covering 6 orders of magnitude of propellant weight were compiled including those from Wierick[2] (Sandia), Lee et al[3] (LLNL), Merrill[4] (AFRPL) using a Titan III C rocket motor weighing 82000 lbs and the Ullian data. These results, all converted to steel impact, are shown in Figure 2 which correlates impact velocity vs. propellant weight with TNT equivalent as a parameter and represents a general steel impact requirement for Class 1.3 propellant.

Figure 2 is the desired detonation requirement correlation; the curves are taken to represent a 50% probability of detonation for a given equivalent. The variability around this midpoint is determined from a log-normal distribution, developed by Hercules for Class 1.1 propellants, from which the standard deviation is determined[5]. Thus the probability of various TNT equivalents resulting from any propellant fragment, at any impact velocity, can be computed.

**AXIAL EJECTION - IMPACT VELOCITIES** Based on a detailed examination of the 1982 event it was concluded that due to propellant gas flow restriction near the igniter, the upper (forward dome) bond line failed leading to overpressurization of the entire Kevlar wound case. The motor case disintegrated and the gas pressure, which was able to penetrate between the grain and the liner at the forward end, "unzipped" the grain and ejected it downward toward the witch's hat. The measured pressure was applied to the grain cross-section and decayed to atmospheric in an estimated 4 - 6 msec. From the drop height to the witch's hat using energy conservation and Newton's laws, the velocity at impact was computed. Because the detonation requirement in Figure 2 implies normal impact and the witches' hat is conical, the calculated impact velocity was adjusted by the sine of one-half the cone interior angle.

Detonating weights at the top (in the capsule) and bottom (at the witches' hat) of the cell were correlated to account for the fact that axial ejection leads to detonation at bottom not at the top as discussed above. This was done using a well-known hydrocode called CSQ[6]. Representative values of weights at the bottom were chosen and using J-4 cell geometry the total blast wave impulse on the capsule dome was determined for full detonation at the witches' hat. Again using CSQ, values of weights at the top were chosen and a "centered" detonation at the original location of the motor was allowed to occur (simulating the geometry of an equivalent blast coming from the witches' hat), and the total impulse on the capsule dome was again determined. These results were used to correlate weight at the bottom with weight at the top by eliminating impulse between them.

**RADIAL EJECTION - IMPACT VELOCITIES - FRAGMENT SIZE DISTRIBUTION** It was assumed that when the motor case fails, the internal pressure breaks that portion of the grain not in the upper dome and accelerates the resulting fragments; it was also assumed that acceleration is rapid and therefore that all fragments have the

same velocity. Impact on the steel wall of the capsule causes initiation of detonation of some of the fragments but each fragment impact can be shown to be an independent event that would not sympathetically detonate other fragments.

Because of the complete lack of data, five different approaches to an acceleration model were used to determine impact velocity. A careful review of these methods led to a range of "realistic" velocities; we chose the uppermost values to be conservative.

There are limited data on the size of the fragments produced in a radial failure. In field testing they are gathered only when an operating motor is destroyed deliberately by a FTOS (Flight Termination Ordnance System) or randomly by an unplanned failure of the type being investigated here. In either case, the propellant is burning at the time of the event and it is very difficult to collect propellant fragments after the test. Nevertheless the data collected after three such tests (Peacekeeper Stage III[7], Trident C-4[7] and Small ICBM Stage I[8]) were used in this study.

A fragment size distribution model was developed based on a set of theoretical distributions from various models of crushing and fracture of solids. It was concluded that only the very simplest concept was justified; the exponential distribution. This states that the number of fragments greater than a given size is exponentially related to that size. The existing data above are consistent with this distribution at the higher values of fragment size but there are missing data at lower values. This is understandable since the data collection process was very rough and we may assume that many small-sized fragments are either lost on the ground or are burned-up in the fireball. The distributions were developed by "treating" the data to estimate the "missing" fragments, using the above model and extrapolating "backwards" to zero size. This was used to reconstitute the data and the parameter that fully describes the fragment size distribution for each test (average fragment size), was determined. This quantity was shown to correlate well with web thickness for the three data sets above and the resulting expression was applied to the current rocket motor.

The fragment size distribution was converted to a fragment weight distribution by mathematically relating average size to average weight. Thus the fragment size/weight distribution is fully described at any time.

Calculations show that radial failure leads mainly to many small fragments. This is qualitatively consistent with the available post-test data and available films of two of the tests.

**PROBABILITY CALCULATIONS - AXIAL EJECTION** At any time, the propellant weight impacting the witches' hat is known for the full and partial axial cases respectively. The velocity of impact is to be compared to the velocity requirement specified in Figure 2. The procedure is as follows. Weights of TNT outside the cell that

approximately yield a range of blast pressures at range are chosen. These weights are converted to weights at the top of the cell using the inherently conservative assumption of a "paper" capsule. That is, it is assumed that the capsule dome is removed in such a way that it does not extract any energy from the blast inside the cell. Using the weight at the top versus weight at the bottom correlation, the TNT equivalent is defined for each value of weight at the bottom.

The velocity required for 50% probability of detonation is read from Figure 2. From this and the log-normal distribution, the probability that this amount of propellant will detonate is determined. This calculation conservatively determines the probability of detonating this amount or more and is the appropriate calculation. Integration over the burn time gives the desired probability.

The same reasoning applies to axial partial grain ejection except that for each value of weight at the bottom the time integration has to be performed for each value of the fraction of the grain ejected which is itself a random variable. Thus for partial axial ejection a double integration is required.

**PROBABILITY CALCULATIONS - RADIAL EJECTION** This failure mode is qualitatively different from the axial ejection case in that a distribution of fragment sizes is produced (as opposed to a "single" fragment) and that each fragment must be evaluated as a separate impact event. This is treated as follows.

For a given time of failure the web thickness and weight ejected are defined. The fragment weight distribution is given by the cumulative exponential distribution function. For a chosen fragment weight band the mean fragment weight is computed and the number of fragments in the band is determined using the exponential distribution function. The radial impact velocity is compared to that required for 50% probability of detonation from Figure 2 which depends on the fragment weight and the TNT equivalent that is assumed to prevail. From the log-normal distribution the probability can be calculated. A complication occurs because the TNT equivalent is not known. This was resolved by adopting an approach which finds the TNT equivalent that gives the maximum value of the product of the TNT equivalent and the probability. This gives the most weight detonating, a conservative assumption. Once known the mean amount detonating for the fragment is known.

Because there are several fragments in each band, the number of fragments detonating is binomially distributed which is assumed to be approximated by a normal distribution with the same mean and variance. This describes the statistical properties of the weight detonating for the given weight band. To generalize to all fragments at any time, this is repeated for all other weight bands of interest each of which has its own mean and variance for the amount detonating. Because these distributions are approximated by normal distributions, and the sum of normal distributions is a

normal distribution with a mean equal to the sum of the means and a variance equal to the sum of the variances, the distribution of detonating weight for all bands is defined. These distributions are expressed as the cumulative normal distribution of the probability of a given weight, or greater, detonating vs. the weight detonating.

This procedure is generalized for several values of time over the burn time. These are used to plot the probability of detonating a chosen set of weights, or greater, vs. time. Integration of this curve for each of the chosen weights, gives the desired result.

**OVERALL PROBABILITY ASSESSMENT** Expressions for the three additive terms in the probability chain equation were developed and applied to a series of chosen values for weight detonating at the top of the cell. These are combined to yield the value of the probability of a given weight, or greater, detonating. The results show that; (1) radial ejection contributes very little to the overall probability because of the large number of small fragments generated in this failure mode and (2) the axial failure mode probabilities decrease very rapidly. The overall probability thereby also decreases sharply.

The calculated probabilities for selected values of weight at the top are plotted on Figure 3 which is a standard probability assessment chart used by AEDC. When compared to the estimated containment value for J-4 (hatched area in Figure 3) it is seen that the probability of exceeding the cell containment limit is less than one in a million! Thus damage other than to J-4 itself is considered highly improbable (seen as category E in Figure 3).

These results show that the probability of exceeding a significant explosive yield in J-4, and thus in doing much damage to nearby facilities, is very low. It is concluded that it is safe to resume testing in J-4 with these rocket motors.

**ACKNOWLEDGEMENT** This study was the result of the combined efforts of a team of collaborators. The author was just one of the team and wishes to recognize the substantial contributions of Dr. Hoyt Andersen (detonability issues), Stanton Fink (CSQ calculations), Dr. Richard Hoar (structural issues), Clint Jaco (fragment velocity calculations), Graham Morgan (pioneering fragment velocity analysis) and Gus Soux (probability and statistics) to this effort. It would truly not have been possible without them.

**REFERENCES**

1. Louis J. Ullian, "Detonability of Large Solid Rocket Motors," ESMC/SEM Report #84-1, Patrick Air Force Base, Florida, 10 August 1984.

2. L. J. Weirick and D. W. Dugan. "Characterization of Morton-Thiokol Booster-Rocket Propellant TP-H1207C and its Simulant H-19," SAND88-0930, Sandia National Laboratories/Albuquerque, New Mexico, May 1989.

3. LeRoy Green, Edward James and Edward Lee, "The Detonability of Composite Propellants," UCRL-94174 Preprint, Lawrence Livermore National Laboratory, February 24, 1986, (presented at the JANNAF Propulsion Systems Hazards Meeting, Monterey CA, March 3-7, 1986).

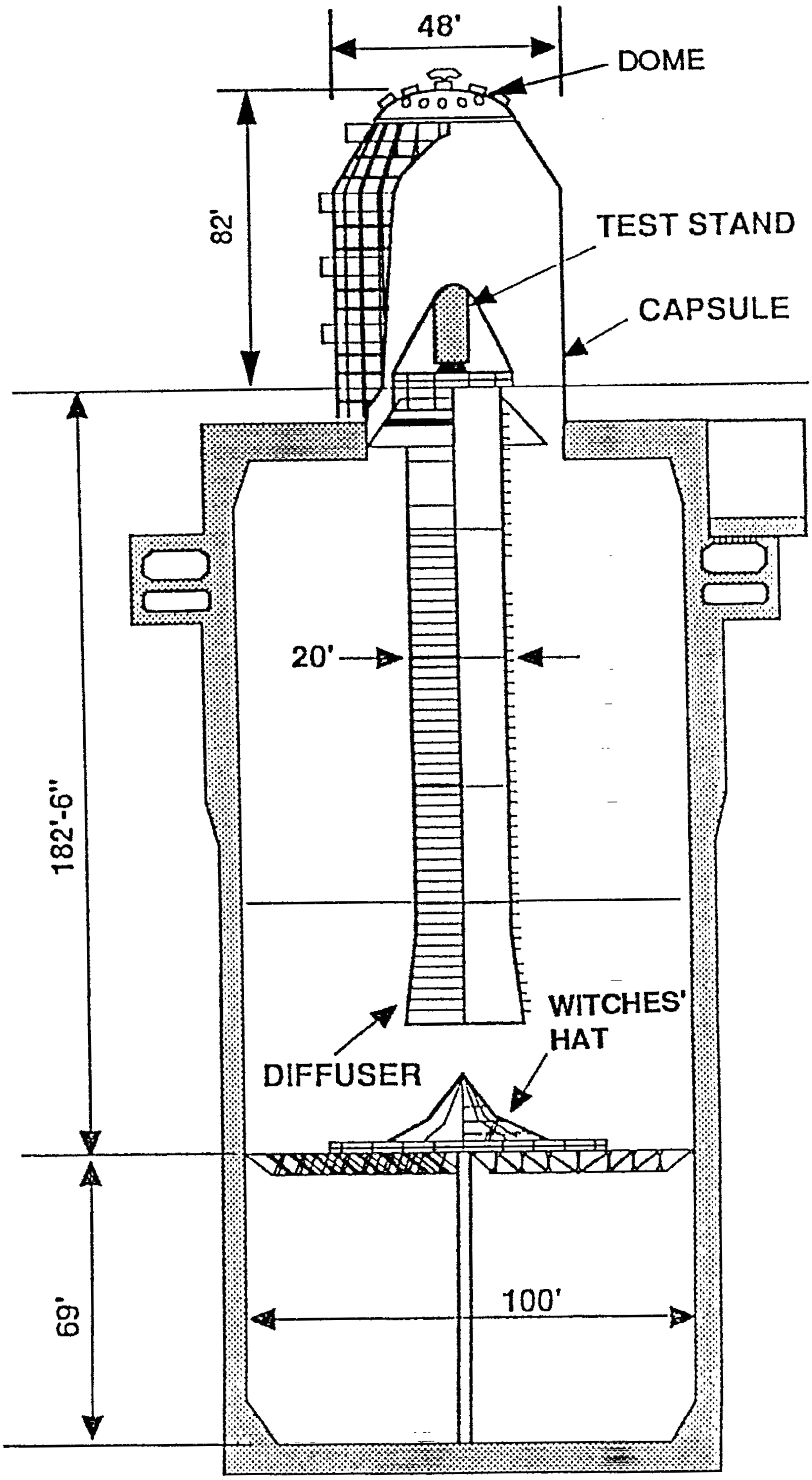
4. (Quoted by Dr. Claude Merrill) Robert F. Vorwerk and Frederick H. Weal, "624A Solid-Propellant Motor Impact Test", Technical Progress Report 381, NOTS TP 3674, U. S. Naval Ordnance Test Station, China Lake, California, October 1964.

5. D.E. Richardson to K. J. Dickerson, "Critical Impact Velocity for Peacekeeper Stage III (T&H and Rail Garrison Applications)," Interoffice Memo SS-1192-88-9617P, Hercules Incorporated, Bacchus Works, Magna, Utah, 06 May 1988.

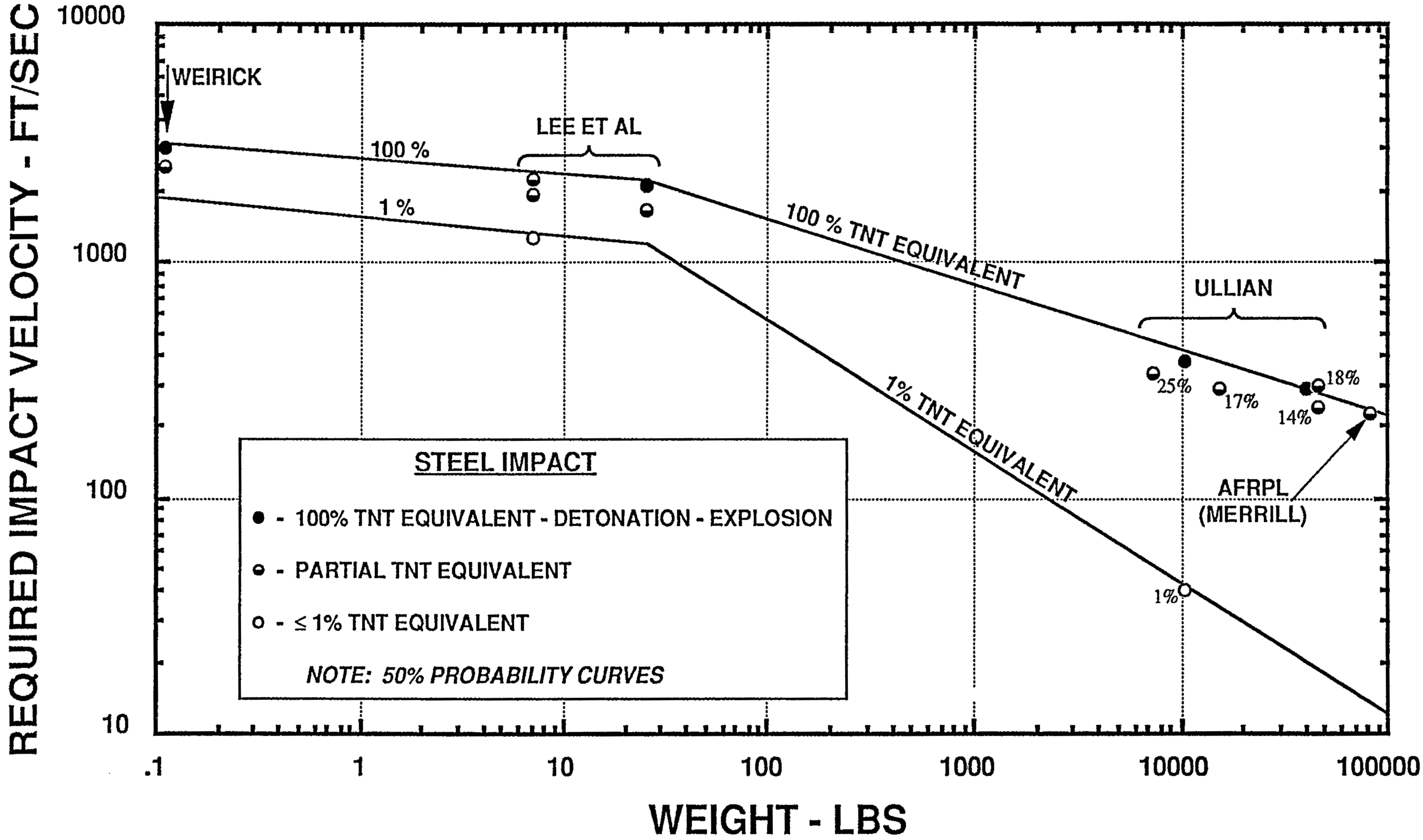
6. S. L. Thompson, "CSQII - An Eulerian Finite Difference Program for Two-Dimensional Material Response - Part 1, Material Sections," SAND77-1339, Sandia National Laboratories, June 1984.

7. J. M. Anderson to S. C. Browning, "Report on Trip to Witness MX DT-01 Destruct Test at AFRPL," Interoffice Memo 0012/6/20-0746, Hercules Incorporated, Bacchus Works, Magna Utah, 23 March 1982.

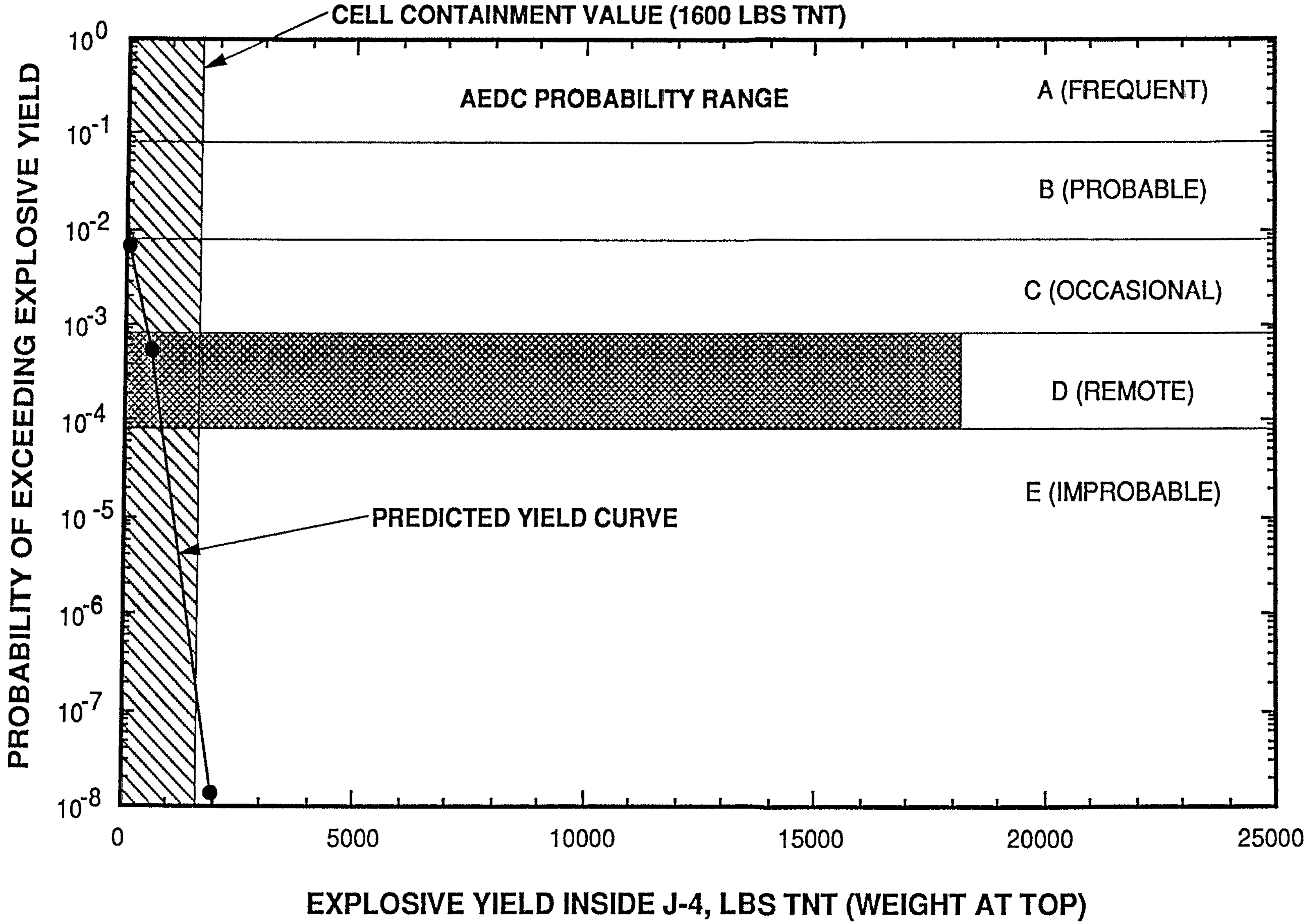
8. R. W. Darr, "Final Test Report for SICBM Stage I Command Destruct Test," TWR-90596, Morton Thiokol, Inc., Wasatch Operations, Brigham City, Utah, 12 December 1987.




# Figure 1 - J-4 Test Cell




# Figure 2 - Detonation Probability Correlation




# Figure 3 - Probability Assessment